Eur. Phys. J. C 50, 603–608 (2007)
DOI 10.1140/epjc/s10052-007-0227-5

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article – Theoretical Physics

The leading particle effect from light quark fragmentation in charm hadroproduction

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Received: 6 July 2006 /
Published online: 17 February 2007 –

Abstract. The asymmetry of D^- and D^+ meson production in $\pi^- N$ scattering observed by the E791 experiment is a phenomenon typical for what is known as the leading particle effect in charm hadroproduction. We show that the phenomenon can be explained by the effect of light quark fragmentation into charmed hadrons (LQF). Meanwhile, the size of the LQF effect is estimated from the data of the E791 experiment. A comparison is made with the estimate of the LQF effect from the prompt like-sign dimuon rate in neutrino experiments. The influence of the LQF effect on the measurement of the nucleon strange distribution asymmetry from charged current charm production processes is briefly discussed.

PACS. 14.60.Pq; 12.15.Ff

1 Introduction

The leading particle effect in charm hadroproduction has been observed by many experiments [1–8]. The main feature of this effect is the enhancement in the production of the charmed hadrons that carry the same valence flavor of the incident hadron in the forward region, i.e., at positive x_F, where x_F is the Feynman variable for the produced hadron, $x_\mathrm{F} \equiv P_z^*/P_z^{*\,\max}$, with P_z^* being the momentum along the beam direction in the c.m. frame of the colliding hadrons. The result of the E791 experiment [3] is a typical example of such a phenomenon with high statistics. In the E791 experiment, a 500 GeV $\pi^-(\bar{u}d)$ beam is incident on a fixed target, and an obvious excess of $D^-(\bar{c}d)$ (having the same valence flavor d as π^-) over $D^+(c\bar{d})$ has been observed. The asymmetry variable

$$A \equiv \frac{\mathrm{d}\sigma(D^-) - \mathrm{d}\sigma(D^+)}{\mathrm{d}\sigma(D^-) + \mathrm{d}\sigma(D^+)} \qquad (1)$$

versus x_F and P_T^2 is used to describe the effect, and a clear rise of the asymmetry A with x_F has been observed.

On the theoretical side, because perturbative QCD (PQCD) predicts no asymmetry at leading order (LO) and a very small asymmetry at next to leading order (NLO) for charm and anticharm quark production [9, 10], the observed asymmetry is generally attributed to the hadronization processes. The "beam drag effect" [11] implemented in the PYTHIA Monte Carlo explains the asymmetry by the color strings between the produced charmed quarks and the beam remnants that move in the same general direction. The charmed hadron produced through the decay/collapse of the low mass string may have more energy than the original charmed quark because of the pull of the fast beam remnants. By adjusting some parameters of the model, they can reproduce the observed asymmetry. Another explanation is the intrinsic charm coalescence model [12], in which an intrinsic charm quark of the projectile combines a valence quark of similar rapidity to form the charmed leading particle. However, this model predicts a much smaller asymmetry than what is observed experimentally. Further, we have the heavy quark recombination mechanism [13], in which a produced heavy (anti-) quark recombines with a light parton of similar velocity that participates in the hard scattering process. The work cited employs a simple PQCD $O(\alpha_\mathrm{s}^3)$ picture and describes the high x_F and P_T^2 distributions of the asymmetry very well. There are still other works on quark recombination and the quark–gluon string model [14, 15].

Although so much work has been done, we should still explore other possibilities. As first promoted by Dias de Deus and Durães [16] in this field, we investigate the possible contribution of light quark fragmentation (LQF) into charmed hadrons. The LQF effect is an old idea, originally suggested by Godbole and Roy [17–19] to explain the unexpected high rate of prompt like-sign dimuon production from many neutrino experiments [20, 21]. Although there are deviations in the experiments, and later high statistics experiments tend to show a smaller effect than earlier experiments, the LQF effect could not be ruled out ex-

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perimentally. When the leading particle effect in charm hadroproduction is observed, Dias de Deus and Durães [16] point out, the generally neglected fragmentation process, e.g. $d \to D^-(\bar{c}d)$, could be a possible mechanism to explain the observed asymmetry. When the NuTeV anomaly [22, 23] is shown to be settled by the nucleon strange asymmetry [24–31], as hopefully will happen, while on the other hand, CCFR and NuTeV measurements do not show evidence for the strangeness asymmetry [32, 33], we point out that the LQF effect possibly will influence such measurements [34]. In this paper, we will investigate the LQF effect in charm hadroproduction and estimate the size of the LQF effect from the E791 experiment. In Sect. 2, we will describe the physical mechanism of the LQF effect and present its parametrization. A detailed description of our calculation will be given in Sect. 3. The results will be shown and discussed in Sect. 4. In Sect. 5 we will give a summary and our conclusions.

2 The LQF effect

In our model of the LQF effect, we differentiate the favored fragmentation $q \to \bar{D}(\bar{c}q)$ or $\bar{q} \to D(c\bar{q})$, which is non-negligible, from the unfavored fragmentation, e.g., $q \to D(c\bar{q}')$, which could be an indirect effect from LQF due to charm flavor conservation, and which can be neglected, since it is mainly confined near target area, i.e., in the case of large negative x_{F}, where experiments were intangible. In $\pi^- N$ scattering, for example, since there are more d quarks than $\bar{d}$ quarks in π^-, more d than $\bar{d}$ will participate in the hard scattering, and with the favored fragmentation of $d \to D^-(\bar{c}d)$ and $\bar{d} \to D^+(c\bar{d})$, more D^- than D^+ will be produced in the forward region; this is in accord with what is observed in experiments.

In this work, the picture of the LQF effect has some differences with works of other authors. We propose a pick-up mechanism for the light quark fragmentation. After hard scattering of subprocesses, the outgoing light quark will experience a period of hadronization. This period, $\Delta T \sim 1/M$, is relatively long compared to some processes with large energy transfer, $\Delta t \sim 1/\Delta E$. Then, through large momentum transfer of the strong interaction, the outgoing light quark can pick up a charmed (anti-) quark from the nucleon sea, forming a cluster, which can then decay into a charmed hadron.

Although in the pick-up process, the light quark gives most of its energy and momentum to the nucleon system, the Q^2 of the interaction can be very small along the initial quark direction, and thus the process is actually a non-perturbative one and is not largely suppressed by $\alpha_{\mathrm{s}}(Q^2)$. For a rough estimate, one can consider a massless outgoing light quark with energy E_q in the nucleon rest frame. Through the pick-up process, the light quark turns into a constituent one (with constituent mass about 0.3 GeV) of the produced D meson along its initial direction. It is easy to get the squared momentum transfer $Q^2 \sim 0.5\,\mathrm{GeV}^2$. The lowest momentum fraction of the charmed sea from the nucleon in this process should be $\xi \sim m_c/\Delta E_q$, and the size of the LQF effect is roughly proportional to the number of charmed sea particles above ξ, $n_c \sim \int_\xi^1 c(x)\,\mathrm{d}x$. This will yield a E_q dependence of the LQF effect that is nearly a linear rise with E_q. This trend is consistent with the observed prompt like-sign dimuon rates in the experiments [20, 21].

From the pick-up process, the outgoing light quark can hadronize into a charmed hadron with a fraction z of its initial energy along its initial direction in the nucleon rest frame. The flavor of the light quark is most probably a valence flavor of the produced hadron.

For a quantitative estimate of the LQF effect, we construct the parametrization of the light quark fragmentation function $D_d^{D^-}(z, E_q)$, which describes the fragmentation of a light quark d into a D^- meson (including D^- from D^{*-} decay), with E_q and z being the energy of the light quark and the energy fraction of the produced D^- meson, $z \equiv E_D/E_q$, in the nucleon rest frame. We assume charge symmetry, $D_d^{D^-}(z, E_q) = D_{\bar{d}}^{D^+}(z, E_q) \equiv D_f(z, E_q)$, and we take $D_f(z, E_q) = C(E_q)P(z)$, where $P(z)$ is a normalized parametrization, and we use the form $P(z) \propto z^\alpha(1-z)$ [35] with α being a free parameter. The form of $C(E_q)$ should correspond to an approximately linear rise as we have mentioned. We take the form $C(E_q) = a(E_q - E_0)$ when $E_q > E_0$, where E_0 corresponds to the energy threshold for the LQF effect. We also assume suppression for the fragmentation of low transverse momentum light quarks, which corresponds to remote interactions. Thus we include the suppression factor $(1 - m_H^2/p_{q\mathrm{T}}^2)$ with the restriction $p_{q\mathrm{T}}^2 > m_H^2$, where m_H is the mass of the produced hadron, and $p_{q\mathrm{T}}$ is the transverse momentum of the light quark. From the above, we get the form of the light quark fragmentation function:

$$D_f(z, E_q) = a(E_q - E_0)\big(1 - m_H^2/p_{q\mathrm{T}}^2\big)P(z, \alpha)\,, \qquad (2)$$

where E_0, a and α are parameters that describe the size and the form of the LQF effect.

3 Calculations for charm hadroproduction

For high energy hard scattering of hadrons A and B, the inclusive cross section for the production of hadron C can be factorized as

$$\frac{E_C\,\mathrm{d}^3\sigma_{AB\to CX}}{\mathrm{d}^3\mathbf{P}_C} = \sum_{abcd}\int \mathrm{d}x_1\,\mathrm{d}x_2 f_A^a(x_1, Q^2) f_B^b(x_2, Q^2) \times \frac{\mathrm{d}\hat{\sigma}_{ab\to cd}}{\mathrm{d}\hat{t}} D_c^C(z, Q^2)\frac{1}{\pi z}\,, \qquad (3)$$

where $f_A^a(x_1, Q^2)$ and $f_B^b(x_2, Q^2)$ are the parton distribution functions, with x_i being the momentum fraction carried by the parton in the infinite momentum frame. $\frac{\mathrm{d}\hat{\sigma}_{ab\to cd}}{\mathrm{d}\hat{t}}$ is the cross section of the subprocess, with $\hat{t}$ being the parton level Mandelstam variable. $D_c^C(z, Q^2)$ is the fragmentation function of parton c into hadron C, with z being the energy fraction of parton c carried by the hadron C, $z = E_C/E_c$, in the parton c.m. frame. Q^2 is the factorization scale, which can be taken as the squared transverse momentum of the subprocess.

Now we consider the process $\pi^- N \to D^\pm X$. Since a charm hadron is always regarded as the fragmentation product of charmed quarks, with the LO subprocesses $gg \to c\bar{c}$ and $q\bar{q} \to c\bar{c}$ and the charge symmetry assumption $D_c^{D^+}(z,Q^2) = D_{\bar{c}}^{D^-}(z,Q^2)$, the produced D^+ and D^- should be symmetric. However, if the light quark fragmentation into charmed hadrons is non-negligible, the additional contribution from the LQF effect should be considered, according to (3). The largest contributions from the LQF effect are $d+g \to d+g$ with $d \to D^-$, and $\bar{d}+g \to \bar{d}+g$ with $\bar{d} \to D^+$. Since more d than $\bar{d}$ quarks exist in π^- and the nucleon, more d than $\bar{d}$ quarks will contribute to the process, and more D^- than D^+ will be produced, just as experimentally observed.

The LO PQCD calculation of charm hadroproduction for fixed target experiments with factorization formulae is a debated area, since Q^2 is generally only a few GeV^2 in this energy region, and higher order corrections could be large. The NLO calculation [10] produces an increasing factor of about 2 relative to the LO calculation, with a similar form for the differential cross sections. However, since we only aim at a sketchy estimate of the LQF effect in this work, and since the asymmetry of (1), which we calculate, is a ratio of the cross sections, whose uncertainties may be cancelled to some extent, we expect reasonable results within the uncertainties from the LO calculation.

The differential cross section for the inclusive production of hadron C as a function of x_F can be expressed as

$$\frac{\mathrm{d}\sigma_{AB\to CX}}{\mathrm{d}x_\mathrm{F}} = \sum_{abcd} \int \mathrm{d}x_1\,\mathrm{d}x_2\,\mathrm{d}z f_A^a(x_1,Q^2) f_B^b(x_2,Q^2) \times \frac{\mathrm{d}\hat{\sigma}_{ab\to cd}}{\mathrm{d}\hat{t}} D_c^C(z,Q^2) \left|\frac{\mathrm{d}x_\mathrm{F}}{\mathrm{d}\hat{t}}\right|^{-1}, \quad (4)$$

where x_F is the Feynman variable for hadron C, $x_\mathrm{F} = 2P_z^*/\sqrt{S}$, with P_z^* being the momentum along the incident direction in the c.m. frame of the interacting hadrons A and B, and S is the squared center of mass energy $S = (P_A + P_B)^2$.

When the masses of quarks and hadrons are neglected, $P_C = zp_c$ will hold in any reference frame, and x_F can be expressed as

$$x_\mathrm{F} = z\frac{(x_1+x_2)\hat{t} + x_1\hat{s}}{\hat{s}}, \quad (5)$$

where $\hat{s} = x_1 x_2 S$ is the squared center of mass energy of the subprocess. Thus the term $\left|\frac{\mathrm{d}x_\mathrm{F}}{\mathrm{d}\hat{t}}\right|^{-1}$ in (4) is

$$\left|\frac{\mathrm{d}x_\mathrm{F}}{\mathrm{d}\hat{t}}\right|^{-1} = \frac{x_1 x_2 S}{z(x_1+x_2)}. \quad (6)$$

However, the masses of c quark and $D^\pm$ meson should be considered in our case, and their effects can be taken as corrections to (5) and (6). The corrections are different for charmed quark fragmentation and light quark fragmentation into charmed hadrons.

In the case of charmed quark fragmentation, with consideration of the charmed quark mass m_c and the produced charmed hadron mass m_H, (5) and (6) can be corrected as follows:

$$x_\mathrm{F} = z\frac{x_1 - x_2}{2} + z'\frac{x_1+x_2}{\hat{s}}\left(\hat{t} - m_c^2 + \frac{\hat{s}}{2}\right), \quad (7)$$

and

$$\left|\frac{\mathrm{d}x_\mathrm{F}}{\mathrm{d}\hat{t}}\right|^{-1} = \frac{x_1 x_2 S}{z'(x_1+x_2)}, \quad (8)$$

where $z' = z(1 - \epsilon_H + \epsilon_c)$, with $\epsilon_H = 2m_H^2/(z^2\hat{s})$ and $\epsilon_c = 2m_c^2/\hat{s}$.

In the case of light quark fragmentation, when the produced charmed hadron mass m_H is considered, and we may notice that the fragmentation function is defined in the nucleon rest frame with z being the energy fraction of the produced hadron, (5) and (6) can be corrected as follows:

$$x_\mathrm{F} = z\frac{(x_1+x_2)\hat{t} + x_1\hat{s}}{\hat{s}} - 2z\epsilon_H^N \frac{(E_A+M)p_{qz}}{S}, \quad (9)$$

and

$$\left|\frac{\mathrm{d}x_\mathrm{F}}{\mathrm{d}\hat{t}}\right|^{-1} = \left[z\frac{x_1+x_2}{\hat{s}} + \frac{z\epsilon_H^N x_1 E_A}{M\hat{s}}\left(\frac{2p_{qz}}{E_q} - 1\right)\right]^{-1}, \quad (10)$$

where E_A is the incident energy, which is 500 GeV for the π^- beam in the E791 experiment, and M is the mass of the target nucleon; $\epsilon_H^N \equiv m_H^2/(2z^2E_q^2)$, and E_q and p_{qz} are the energy and longitudinal momentum of the outgoing light quark in the nucleon rest frame,

$$E_q = x_1 E_A\left(1 + \frac{\hat{t}}{\hat{s}}\right) + \frac{x_2 M}{2}, \quad (11)$$

$$p_{qz} = (x_1 E_A + x_2 M)\frac{\hat{t}}{\hat{s}} + x_1 E_A + \frac{x_2 M}{2}. \quad (12)$$

Similarly, the differential cross section as a function of P_T^2 can be expressed by

$$\frac{\mathrm{d}\sigma_{AB\to CX}}{\mathrm{d}P_\mathrm{T}^2} = \sum_{abcd} \int \mathrm{d}x_1\,\mathrm{d}x_2\,\mathrm{d}z f_A^a(x_1,Q^2) f_B^b(x_2,Q^2) \times \frac{\mathrm{d}\hat{\sigma}_{ab\to cd}}{\mathrm{d}\hat{t}} D_c^C(z,Q^2) \left|\frac{\mathrm{d}P_\mathrm{T}^2}{\mathrm{d}\hat{t}}\right|^{-1}. \quad (13)$$

When the mass effect is neglected, P_T^2 and $\left|\frac{\mathrm{d}P_\mathrm{T}^2}{\mathrm{d}\hat{t}}\right|^{-1}$ can be expressed as

$$P_\mathrm{T}^2 = -z^2\left(\frac{\hat{t}^2}{\hat{s}} + \hat{t}\right) \quad (14)$$

and

$$\left|\frac{\mathrm{d}P_\mathrm{T}^2}{\mathrm{d}\hat{t}}\right|^{-1} = \frac{\hat{s}}{z^2|\hat{s} + 2\hat{t}|}. \quad (15)$$

In the case of charm quark fragmentation, with the inclusion of the mass effect, (14) and (15) can be corrected as follows:

$$P_\mathrm{T}^2 = -z'^2\left[\frac{\left(\hat{t} - m_c^2\right)^2}{\hat{s}} + \hat{t}\right], \quad (16)$$

and

$$\left|\frac{\mathrm{d}P_{\mathrm{T}}^2}{\mathrm{d}\hat{t}}\right|^{-1}=\frac{\hat{s}}{z'^2\left|\hat{s}+2\left(\hat{t}-m_c^2\right)\right|}\,, \tag{17}$$

where $z'=z(1-\epsilon_H+\epsilon_c)$, with $\epsilon_H=2m_H^2/(z^2\hat{s})$ and $\epsilon_c=2m_c^2/\hat{s}$. In the case of light quark fragmentation from the nucleon rest frame, with the mass of the produced hadron m_H being considered, (14) and (15) can be corrected as follows:

$$P_{\mathrm{T}}^2=-z^2\left(1-2\epsilon_H^N\right)\left(\frac{\hat{t}^2}{\hat{s}}+\hat{t}\right), \tag{18}$$

and

$$\left|\frac{\mathrm{d}P_{\mathrm{T}}^2}{\mathrm{d}\hat{t}}\right|^{-1}=\frac{\hat{s}}{z^2\left|\hat{s}\left(1-2\epsilon_H^N\right)+2\hat{t}\right|}\,, \tag{19}$$

where $\epsilon_H^N\equiv m_H^2/(2z^2E_q^2)$, and E_q is expressed in (11).

In our calculations, $\hat{s}\geq(2m_H)^2$ and $z\geq 2m_H/\sqrt{\hat{s}}$ are required in $c\bar{c}$ production and fragmentation processes, and $m_H/E_q\leq z\leq 1-(m_{\Lambda_c}-M)/E_q$ is required in light quark fragmentation. To compare our calculation with the E791 data, the restriction $-0.2<x_{\mathrm{F}}<0.8$, just as in the experiment, is necessary in the calculation of the P_{T}^2 distribution. As for the calculation of the x_{F} distribution, P_{T}^2 is indirectly restricted by $Q^2\geq Q_0^2$.

We use the CTEQ6L1 parton distributions [36] for the nucleon, and we employ the LO parametrization forms of [37] for the parton distributions of the π^-. Since the E791 experiment uses a target mainly of carbon, we take it as an isoscalar target for the nucleon parton distributions. We consider the LO subprocesses $gg\to c\bar{c}$ and $q\bar{q}\to c\bar{c}$ for charm quark production and various LO subprocesses, including $qg\to qg$, $qq'\to qq'$, $q\bar{q}\to q\bar{q}$, $qq\to qq$, $q\bar{q}\to q'\bar{q}'$ and $gg\to q\bar{q}$, for the d and $\bar{d}$ light quark production. The cross sections $\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\hat{t}}$ for these subprocesses can be found in [38–40]. We use the LO running α_{s} with $\Lambda_{\mathrm{QCD}}=215\,\mathrm{MeV}$ for $n_f=4$ and $\Lambda_{\mathrm{QCD}}=165\,\mathrm{MeV}$ for $n_f=5$, as specified in CTEQ6L1. We set the factorization scale $Q^2=p_{c\mathrm{T}}^2+m_c^2$ for the charm quark production processes, and $Q^2=p_{q\mathrm{T}}^2$ for light quark production processes, with $m_c=1.5\,\mathrm{GeV}$ and $Q_0^2=m_H^2\approx 3.5\,\mathrm{GeV}^2$, where $p_{q\mathrm{T}}$ is the transverse momentum of quark q. We use the Peterson parametrization [41] for the charm fragmentation function $D_c^D(z,\epsilon_P)$, with $\epsilon_P=0.08$, and the fragmentation fraction 0.23 for $c\to D^+$ (including D^+ from D^{*+} decay) [42, 43]. For the light quark fragmentation $d\to D^-$ and $\bar{d}\to D^+$, we use the parametrization of (2) and tune the parameters to describe the observed asymmetry.

4 Results and discussions

From numerical calculations we can find good descriptions of the observed asymmetry from the E791 experiment. Figure 1 shows a set of the best fits for both x_{F} and P_{T}^2 distributions with the following parameters: $E_0=40\,\mathrm{GeV}$, $a=2.0\times10^{-5}\,\mathrm{GeV}^{-1}$, and $\alpha=0.6$. Notice that our $A(x_{\mathrm{F}})$ result is consistent with the data of the whole x_{F} region, while the result for $A(P_{\mathrm{T}}^2)$ could not give a good description of the data below $P_{\mathrm{T}}^2\sim 2\,\mathrm{GeV}^2$. This discrepancy, however, can be attributed to the unaccounted for small random transverse momentum of the hadron produced relative to the direction of the light quark when it fragments. When this effect is considered, the sharp peak of $D^\pm$ produced from LQF at low transverse momentum could become broader, and the asymmetry curve should get greatly balanced at low P_{T}^2. Meanwhile, the general features of $A(x_{\mathrm{F}})$ and $A(P_{\mathrm{T}}^2)$ ($P_{\mathrm{T}}^2>2$) do not change.

E_0 is the parameter that describes the energy threshold for light quark fragmentation into charmed hadrons. There are still uncertainties in its value, as our result is insensitive to this. Nevertheless, the overall size of the LQF effect (about $a(E_q-E_0)$) is quite stable in our fits when changing E_0 from 10 to 80 GeV; it is about 2.4×10^{-3} near $E_q=160\,\mathrm{GeV}$, which is the typical energy under study. α describes the shape of the fragmentation function for

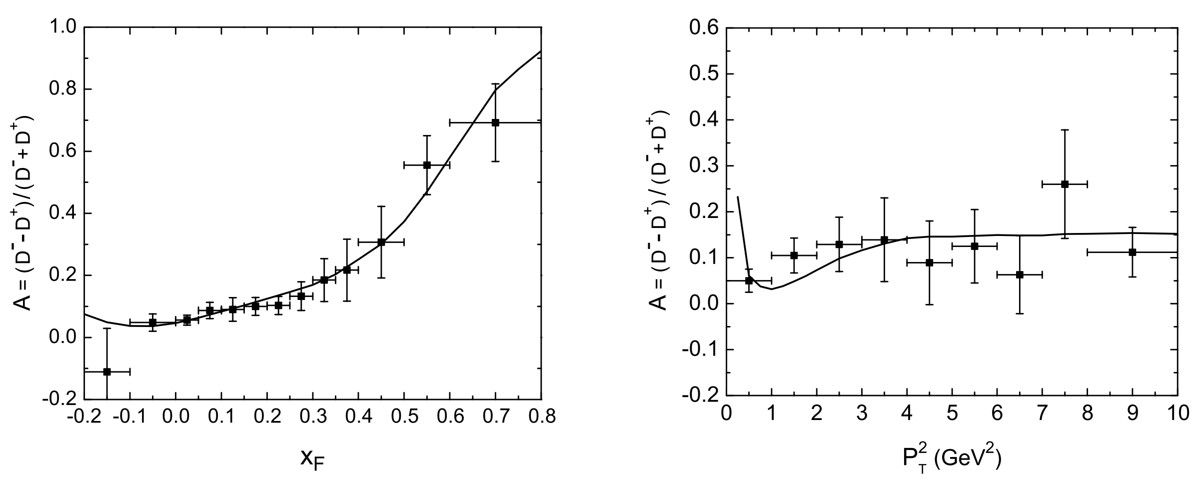

Fig. 1. Comparison of the asymmetry variable of (1) from the LQF effect of this work with the E791 data [3]. The *solid lines* are the results of our calculation with parameters $E_0=40$ GeV, $a=2.0\times10^{-5}$ GeV^{-1}, and $\alpha=0.6$

the LQF effect, and $\alpha = 0.6$ corresponds to a broad peak around $z = 0.4$.

In this work, we attribute the leading particle effect for charm hadroproduction to the LQF effect from the pick-up process of the produced light quarks. Nevertheless, we do not exclude other possible contributions that lead to the fragmentation of light quark into charmed hadrons, which should still be explored by some dedicated work.

From our LO calculation, the LQF effect could give a good description of the observed $D^{\pm}$ asymmetry. On the other hand, we can get an estimate of the shape and the size of the LQF effect from the fitting results. When z is integrated out, the size of the LQF effect can be drawn from (2) to be found to be about $a(E_q - E_0)$, when $p_{q\mathrm{T}}^2 \gg m_H^2$, with $E_0 = 40\,\mathrm{GeV}$ and $a = 2.0 \times 10^{-5}\,\mathrm{GeV}^{-1}$, and one gets $D_f(E_q) = 2(E_q - 40) \times 10^{-5}$. For the typical value $E_q = 160\,\mathrm{GeV}$, one gets $D_f = 2.4 \times 10^{-3}$, which is very stable in our fit as we have mentioned above. However, there are still uncertainties for this fitting result both from LO calculations and from the parametrization of the light quark fragmentation function. Since the energy of fixed target experiments is limited, higher order effects will contribute, and the calculated LO cross sections show a scale dependence. Meanwhile, the low transverse momentum suppression factor $(1 - m_H^2/p_{q\mathrm{T}}^2)$ in our parametrization gives an extra uncertainty of a factor of 1/3. As a sketchy estimate, we set an increasing factor of 2 and a decreasing factor of 3 as its uncertainties around the central value of our fit. Thus, for $E_q = 160\,\mathrm{GeV}$, we have an estimate of $0.8 \times 10^{-3} \leq D_f \leq 4.8 \times 10^{-3}$, i.e. $D_f = (2.4^{+2.4}_{-1.6}) \times 10^{-3}$, for the size of the LQF effect.

Now we compare our result with the previous estimate of the LQF effect from the neutrino induced dimuon production process [34]. In the previous work, the light quark fragmentation rate, defined by $D_q \equiv D_q^D + D_q^{D^*}$, is different from the definition in this work, which is the rate of $d \to D^-$ including D^- from D^{*-} decay, i.e., $D_f = D_q^D + B^* D_q^{D^*}$, where D_q^D and $D_q^{D^*}$ indicate direct fragmentation into a D or D^* meson from light quarks, and $B^* \approx 1/3$ is the fraction for D^{*-} decay to D^- [44]. With an estimate for the ratio $D_q^{D^*}/D_q^D = 3/1$ from spin counting, we find that the D_q in the previous work should be one half smaller when it is compared to D_f in this work. D_q can be taken from (13) of [34], $D_q/\bar{f}_c \approx 0.20\,\sigma_{\mu^-\mu^-}/\sigma_{\mu^-\mu^+}$, with an estimate of $\bar{f}_c = 0.86$ and taking $\sigma_{\mu^-\mu^-}/\sigma_{\mu^-\mu^+} = (3.5 \pm 1.6)\%$ [20], which is the prompt dimuon rate for $100 < E_{\mathrm{vis}} < 200\,\mathrm{GeV}$ with the cut $p_\mu > 6\,\mathrm{GeV}$. From the above, one can get $D_q = (6.0 \pm 2.7) \times 10^{-3}$. Now we can compare $\frac{1}{2} D_q = (3.0 \pm 1.4) \times 10^{-3}$ with $D_f(E_q = 160\,\mathrm{GeV}) = (2.4^{+2.4}_{-1.6}) \times 10^{-3}$, for they have a similar energy range. From the above, we find that the size of the LQF effect from the estimate of this work of charm hadroproduction is a little smaller but consistent with that of the estimate from the neutrino induced prompt $\mu^-\mu^-$ production process. The estimation of the LQF effect from $\mu^+\mu^+$ data in the previous work yields a much larger size, which is not supported by this work.

In our previous work [34], we have shown that the LQF effect could influence the measurement of the nucleon strange asymmetry by charged current charm production processes. When the LQF effect is large enough, it can balance the effect from the nucleon strange asymmetry, which could explain why CCFR and NuTeV experiments do not show evidence for the nucleon strange asymmetry. From the estimate of the LQF effect in this work, the size of the LQF effect at $E_q = 160\,\mathrm{GeV}$ is about $(2.4^{+2.4}_{-1.6}) \times 10^{-3}$, which is still twice or more smaller to compensate the predicted nucleon strange asymmetry that can explain the NuTeV anomaly [27–31]. However, in the CCFR and NuTeV experiments (neutrino energy up to 600 GeV), the energy of E_q can be much larger, and the LQF effect may possibly be greatly enhanced. Thus, in CCFR and NuTeV, the LQF effect still possibly influences the measurement of the nucleon strange asymmetry to a large extent. Further study of the LQF effect under various processes will be helpful to further clarify this effect.

5 Summary

In this work, we have attempted to explain the leading particle effect in charm hadroproduction by the picture of light quark fragmentation into charmed hadrons (LQF). We can obtain good descriptions of the observed $D^{\pm}$ asymmetry from the E791 experiment for both the x_{F} and the P_{T}^2 distribution. Although the uncertainty from our LO PQCD calculation is large, we find a total size of the order of 10^{-3} for the LQF effect at a typical energy $E_q = 160\,\mathrm{GeV}$ of the light quark. This result is consistent with the estimate of the LQF effect from the neutrino induced prompt $\mu^-\mu^-$ data in our previous work. The influence of the LQF effect on the measurement of the nucleon strange asymmetry in neutrino induced charged current charm production processes could be non-negligible.

Acknowledgements. We thank Prof. K.-T. Chao, Prof. C.-H. Chang, C. Meng and F. Huang for helpful discussions. This work is partially supported by the National Natural Science Foundation of China (Nos. 10421503, 10575003, 10528510), by the Key Grant Project of Chinese Ministry of Education (No. 305001), and by the Research Fund for the Doctoral Program of Higher Education (China).

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